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THE RELATIVE CONTRIBUTION OF SOIL TILLAGE AND OVERLAND FLOW EROSION TO SOIL REDISTRIBUTION ON AGRICULTURAL LAND

G. GOVERS[1], T. A. QUINE[2], P. J. J. DESMET[1] AND D. E. WALLING[2]

[1] *Laboratory for Experimental Geomorphology, Katholieke Universiteit Leuven, Redingenstraat 16B, 3000 Leuven, Belgium*
[2] *Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, Devon, UK*

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ABSTRACT

This study uses evidence for the long-term (35 years) pattern of soil redistribution within two agricultural fields in the UK to identify the relative importance of tillage and overland flow erosion. Spatially distributed long-term total soil redistribution data for the fields (Dalicott Farm and Rufford Forest Farm) were obtained using the caesium-137 (^{137}Cs) technique. These data were compared with predicted patterns of soil redistribution.

Recent studies have demonstrated that the redistribution of soil by tillage may be described as a diffusive process. A two-component model was, therefore, developed which accounts for soil redistribution by both overland flow and diffusive processes. Comparison of the predicted patterns of overland flow erosion alone with the observed (^{137}Cs-derived) data indicated a poor agreement ($r^2 = 0{\cdot}17$ and $0{\cdot}11$). In contrast, a good agreement exists between the predicted pattern of diffusive redistribution and the observed data ($r^2 = 0{\cdot}43$ and $0{\cdot}41$). These results give a clear indication that diffusive processes are dominant in soil redistribution within these fields. Possible diffusive processes include splash erosion, soil creep and tillage. However, the magnitude of the diffusion coefficients for the optimum predicted pattern (*c.* 350–400 kg m^{-1} a^{-1}) demonstrates that tillage is the only process capable of explaining the very significant soil redistribution which is indicated by the ^{137}Cs data. Consideration is given to the implications of these results for both soil erosion prediction and landscape interpretation.

KEY WORDS soil degradation; caesium-137; tillage; water erosion

INTRODUCTION

The last decade has seen both a continuing interest in the dynamics of soil erosion on agricultural land (cf. Boardman *et al.*, 1990; Wicherek, 1993) and increasing concern for the on-site and off-site impacts (ISRIC, 1992; Clark *et al.*, 1985). Not surprisingly, much of the interest and concern has focused on the impact of water erosion, because this is usually the most visible indicator of soil loss and the most important process contributing to soil export from a cultivated field. However, when considering the rates and pattern of total soil loss and accumulation *within* individual fields it is important to identify all contributing processes and there is growing evidence that the effects of soil tillage should be taken into account (Lindstrom *et al.*, 1992; Govers *et al.*, 1993; Revel *et al.*, 1993; Govers *et al.*, 1994; Quine *et al.*, 1994). In the light of this evidence, there is a clear need to assess the relative importance of water erosion and tillage processes in determining the rates and patterns of total soil redistribution.

This study attempts to address this need through a three-stage process involving: (i) collection of spatially distributed field data which document the pattern of total soil loss and gain; (ii) prediction of the patterns of erosion and deposition at these sites which would result from overland flow erosion and diffusive processes (including tillage (Govers *et al.*, 1994)) and a combination of both; and (iii) differentiation between the impact of tillage and water erosion processes at the field sites by comparison of the measured and predicted

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soil redistribution patterns and evaluation of the rates involved. The requirement for spatially distributed total erosion data is met through application of the caesium-137 (^{137}Cs) technique and the prediction of the patterns of erosion and deposition is addressed through the development of a two-dimensional erosion–deposition model, which employs concepts proposed by Kirkby (1971). These aspects are considered in greater detail in the sections which follow the description of the study sites.

THE STUDY SITES

This study examined two fields, located at Dalicott Farm (Shropshire) and Rufford Forest Farm (Nottinghamshire), which have been described elsewhere (Quine and Walling, 1991, 1993a; Walling and Quine, 1990a, 1991). The characteristics of the fields are summarized in Table I. Both fields lie on sandy soils and are subject to intensive arable cultivation. Furthermore, both fields lie in areas which have been identified by Morgan (1985) as being at risk from erosion and both were chosen for investigation on the basis of a known susceptibility to erosion by water (Evans, pers. comm.). However, the rates of erosion indicated by initial studies using ^{137}Cs at both sites (Quine and Walling, 1991) were higher than expected on the basis of water erosion alone, and Quine and Walling (1993a) have examined evidence for the validity of the erosion rates estimated for the Dalicott site. The sites were, therefore, considered particularly suitable for the current investigation.

Soil samples were collected from the fields using a percussion corer to obtain cores of 38 cm^2 surface area and 60 cm depth (this exceeds the maximum depth to which ^{137}Cs is found at both sites). The cores were collected at the intersections of a 20 m grid which was aligned with respect to the main topographic features within each field. A total of 83 cores were collected from the field at Dalicott and 117 cores from the field at Rufford. The height of each sampling point and the location and height of the field boundaries were also recorded.

DATA COLLECTION USING CAESIUM-137

Background

The ^{137}Cs technique is becoming increasingly recognized as a valuable tool in erosion research (Loughran, 1990) and the growing interest in the ^{137}Cs technique is reflected in a recent review by Ritchie and McHenry (1990) which cites *ca.* 30 papers in which ^{137}Cs has been used in soil loss investigations. Furthermore, a number of authors (cf. Loughran, 1990; Walling and Quine, 1991) have identified the potential advantages of the technique over more conventional approaches to soil loss assessment. In the context of this discussion, the most important characteristics of the technique are the facility to provide data which are (i) spatially distributed; (ii) representative of the net effect of all erosion processes; and (iii) medium-term (35–40 years) average

Table I. Site characteristics for the fields at Rufford Forest and Dalicott Farms

Site	Rufford Forest Farm	Dalicott Farm
Location	SK 614 584	SO 773 944
Soil type	Typical brown sand	Typical brown sand
Soil association	551b Cuckney 1	551a Bridgnorth
Sampled area (ha)	4·7	3·3
Maximum height change (m)	10	16
Slope length (m)		
Maximum	414	390
Mean	83	104
Slope angle (degrees)		
Maximum	9·1	9·3
Mean	3·6	3·0

erosion rates, on the basis of a single site visit. Such information is very difficult and laborious, if not impossible, to obtain using other measurement techniques. The potential value of the ^{137}Cs technique in the investigation of relationships between spatial patterns of erosion and deposition rates and topographic attributes has been demonstrated by Kiss *et al.* (1986), Martz and de Jong (1987), Sutherland (1991) and Quine and Walling (1993b). However, attempts to explain the observed patterns in terms of specific geomorphic processes are scarce and have been essentially qualitative.

The basis and fundamental assumptions of the ^{137}Cs technique have been described in full elsewhere (Walling and Quine, 1991, 1992) and detailed discussion is beyond the scope of this paper. In short, ^{137}Cs inventories (total activity in the soil profile per unit area) measured at the study site are compared with an estimate of the total atmospheric input, which is represented by the mean ^{137}Cs inventory obtained at a 'reference' site. Areas which evidence ^{137}Cs loss are identified as suffering net erosion and, conversely, net ^{137}Cs gain is considered to be indicative of deposition. In order to derive quantitative estimates of erosion it is necessary to establish a site-specific calibration relationship which relates the magnitude of the ^{137}Cs loss to the rate of erosion. As it is rarely possible to establish this using empirical data, the authors have employed a mass-balance model to predict the impact of a range of erosion rates on the ^{137}Cs inventory of a soil profile (see Quine, 1989, 1995). The model makes provision for inclusion of data relating to: the local plough depth and timing of cultivation, potential spatial variation in depth of erosion incision, particle size selectivity of erosion and deposition processes, inter- and intra-annual variation in ^{137}Cs deposition, and the surface accumulation of ^{137}Cs between ploughing events. Furthermore, the model can take account of the impact of erosion by both water and tillage processes. The predicted ^{137}Cs inventories are combined with the specified erosion rates to produce site-specific calibration relationships which are then used to derive estimates of erosion and deposition from the measured ^{137}Cs inventories.

Measurement

All measurements of ^{137}Cs activity which are discussed in this paper were derived using the same procedure. The soil core samples were air-dried, weighed, and disaggregated to separate the <2 mm and >2 mm fractions. Both fractions were weighed and the >2 mm fraction was set aside. All further analysis was conducted on the <2 mm fraction. A sub-sample of this fraction was weighed into a 'marinelli' beaker for analysis. The ^{137}Cs content of this sub-sample was measured by gamma spectrometry using a coaxial germanium detector in the Radionuclide Laboratory of the Department of Geography at the University of Exeter. Caesium-137 was detected at 662 keV and count times were typically *c.* 28 000 s, providing a measurement precision of *c.* ±4 per cent.

Erosion rates derived from caesium-137 data

The distributions of ^{137}Cs inventories for the study sites provide an indication of the pattern of soil movement within the fields, but if the data are to be used in the identification of likely processes it is important to estimate the *rates* of soil redistribution involved. (The ^{137}Cs distributions for the fields at Rufford and Dalicott are illustrated in Walling and Quine (1990a) and (1991), respectively). Each point measurement of ^{137}Cs was, therefore, used to estimate the point erosion or deposition rate using the calibration approach outlined above. These point erosion and deposition rates were then interpolated using UNMAP 2000 (UNIRAS, 1990) to produce the spatial patterns of soil redistribution rates shown in Figure 1. The distributions show distinctive topographic associations, suggesting that comparison with the erosion model results may provide an indication of the dominant processes of erosion operating at the sites.

THE EROSION MODEL

The second stage in the investigation involves the prediction of the patterns of erosion and deposition which would result from water erosion, tillage and a combination of these processes. In order to undertake this, a two-component erosion model has been developed. The first component accounts for overland flow erosion processes, namely rill and interill erosion, and the second component accounts for diffusive processes, which include soil splash and creep as well as tillage (Govers *et al.*, 1994). Because all of the diffusive processes

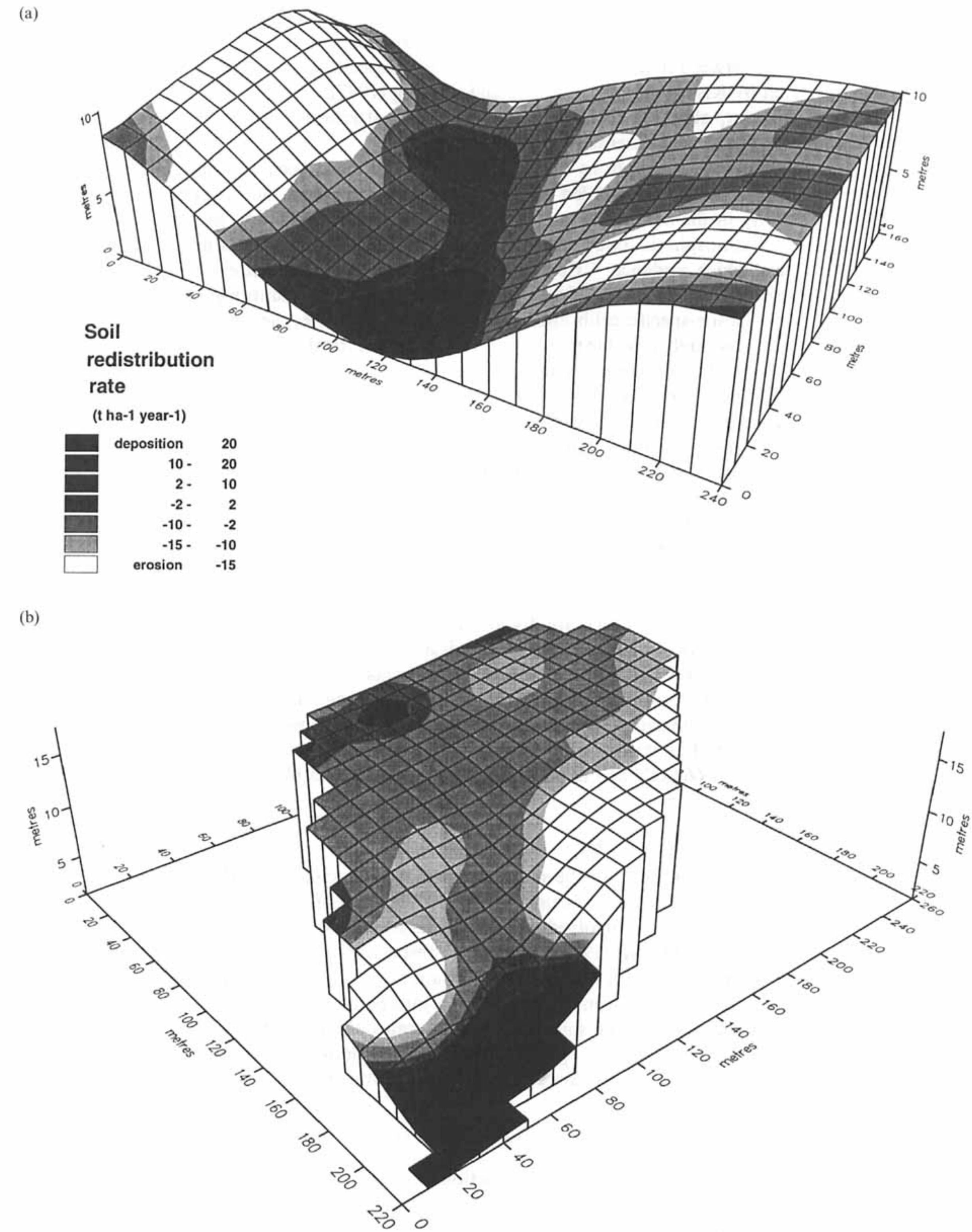


Figure 1. Soil redistribution rates derived from ^{137}Cs inventories superimposed over isometric projections of the field topography for the sites at: (a) Rufford Forest Farm and (b) Dalicott Farm

produce similar *patterns* of soil redistribution, distinction between them must be made on the basis of the *rates* involved and this is addressed in the discussion of the results. The general formulation of the sediment transport rate along a hillslope proposed by Kirkby *et al.* (1987), which accounts for both overland flow and diffusive processes, provides a useful basis for the simulation:

$$Q_s = k_1 \left[1 + \left(\frac{x}{u} \right)^2 \right] S \tag{1}$$

where Q_s = the sediment transport flux (kg m^{-1} a^{-1}), x = the distance from the divide (m), S = the local slope gradient (m m^{-1}), k_1 = the diffusion constant (kg m^{-1} a^{-1}), u = the distance beyond which the overland flow term becomes larger than the diffusion term (m).

The erosion rate for an arbitrary unit of time is then calculated as:

$$E = -\frac{\partial Q_s}{\partial x} \tag{2}$$

where E = the erosion rate (kg m^{-2} a^{-1}).

It should be noted that this formulation assumes that the overland flow erosion process is transport-limited. In the case of the soils under investigation this is not unreasonable, because their sandy nature and low clay content contribute to a low resistance to detachment. However, a more fundamental limitation exists. This is the assumption that on a rectilinear slope the erosion rate due to overland flow is directly proportional to the slope length and slope gradient, whereas empirical results usually suggest that the relationship is better described by a power function, namely:

$$E = -k_2 S^m \left(\frac{x}{x_{\mathrm{ref}}} \right)^n \tag{3}$$

where k_2 = a constant (kg m^{-2} a^{-1}) and x_{ref} = the reference distance (taken as 1 m); which, for a rectilinear slope, corresponds to:

$$Q_{s,w} = k_3 S^m \left(\frac{x}{x_{\mathrm{ref}}} \right)^n x \tag{4}$$

where $Q_{s,w}$ = the sediment transport rate due to erosion by overland flow (kg m^{-1} a^{-1}) and $k_3 = k_2/(n+1)$ (kg m^{-2} a^{-1}).

This leads to a modification of Equation 1 in which the first and second terms describe diffusive and overland flow erosion processes, respectively:

$$Q_s = k_1 S + k_3 S^m \left(\frac{x}{x_{\mathrm{ref}}} \right)^n x \tag{5}$$

or, for a two-dimensional formulation:

$$Q_s = k_1 S + k_3 S^m \left(\frac{A_s}{A_{s_{\mathrm{ref}}}} \right)^n A_s \tag{6}$$

where A_s = the contributing area per unit of contour length (m^2/m), $A_{s_{\mathrm{ref}}}$ = the reference unit contributing area, taken as 1 m^2/m and:

$$E = -\nabla Q_s \tag{7}$$

This modified formulation is preferred because of its agreement with empirical studies and it is, therefore, used in this investigation. Parameterization of these equations was made with reference to both experimental and field studies. The available data with respect to overland flow erosion suggest that the slope length exponent '*n*' (Equation 3) may vary between 0 and 1, with a mean value of *c.* 0·5 (e.g. Zingg, 1940; Musgrave, 1947; Smith and Wischmeier, 1957; McCool *et al.*, 1989; Govers, 1991a). With respect to the slope gradient effect, most studies indicate an exponential increase of overland flow erosion with slope angle, i.e. $m > 1$.

Govers (1991a) found that the relative slope effect when 'm' equals 1·45 is almost identical to the USLE slope factor as proposed by Wischmeier and Smith (1965) and revised by McCool *et al.* (1987). On the basis of these published results a value of 0·5 was used for 'n' and 1·4 for 'm' throughout all model simulations.

Spatially distributed predictions of soil redistribution were obtained by implementing Equation 7 in a grid-based model. Slopes were calculated using the algorithm of Zevenbergen and Thorne (1987), while the contributing area was determined using the multiple flow direction algorithm of Quinn *et al.* (1991). Erosion and deposition rates were calculated as the difference between the calculated outflow and calculated inflow from a cell. Further details about these procedures can be found in Desmet and Govers (in press). On the basis of field observations, the boundaries of both fields were considered to be closed at all points except the potential outlet locations (which correspond to the lowest boundary points).

MODEL APPLICATION

In order to afford an objective comparison with the ^{137}Cs-derived erosion rate estimates (which represent *c.* 30 year averages), the model was always run for 30 iterations, each iteration representing about one year. Furthermore, the following procedure was employed to ensure that the observed (^{137}Cs-derived) and predicted values were of the same magnitude. A calibration parameter 'p' was defined:

$$k_1 = k'_1 p \tag{8}$$

$$k_3 = k'_3 p \tag{9}$$

and introduced into Equation 6:

$$Q_s = p\left[k'_1 S + k'_3 S^m \left(\frac{A_s}{A_{s_{ref}}}\right)^1 A_s\right] \tag{10}$$

Before a run, the relative contribution of diffusive and overland flow processes was defined by fixing the values of k'_1 and k'_3. The value of p was then varied until, after 30 iterations, the slope of the regression between observed (^{137}Cs-derived) and predicted values for each grid cell equalled 1. This sequence was then repeated for a set of values of k'_1 and k'_3. This procedure does not guarantee the best absolute agreement between observed and predicted values because the intercept of the regression equation may be significantly different from zero. However, the approach does ensure that the variation in predicted erosion and deposition rates is of the same order of magnitude as the variation in observed values.

One further safeguard, implemented in the analysis, was the exclusion of all grid intersections which had less than three neighbouring intersections within the field. This reflects the uncertainty associated with predictions of upslope and slope gradient for the excluded points. At Rufford only four points were excluded but, due to the irregular shape of the field, 14 points were excluded from the Dalicott data-set.

Predicted patterns of overland flow

If the parameter k_1 is set to zero then the simulation excludes all diffusive soil movement and the resultant predicted pattern may be identified with overland flow processes. Figure 2, therefore, shows the predicted patterns of erosion rates for Rufford and Dalicott if overland flow is assumed to be the sole cause of soil redistribution. At Rufford, the highest erosion rates are predicted to occur on the steeper midslope sections while local deposition alternates with eroding areas in the shallow sloping thalweg. In contrast, at Dalicott the model predicts a gradual increase of overland flow erosion rates from the divides to the hollow where the highest erosion rates are predicted.

Visual comparison of these predicted distributions (Figure 2) with the observed (^{137}Cs-derived) patterns (Figure 1) shows minimal agreement and this is confirmed by correlation analysis (Table II). This poor agreement reflects the contrasts in the location of the zones of maximum erosion between the observed and predicted distributions. At both Rufford and Dalicott, the zones of maximum observed erosion occur on the upslope convexities where slope gradient is moderate and the upslope area is limited. In contrast,

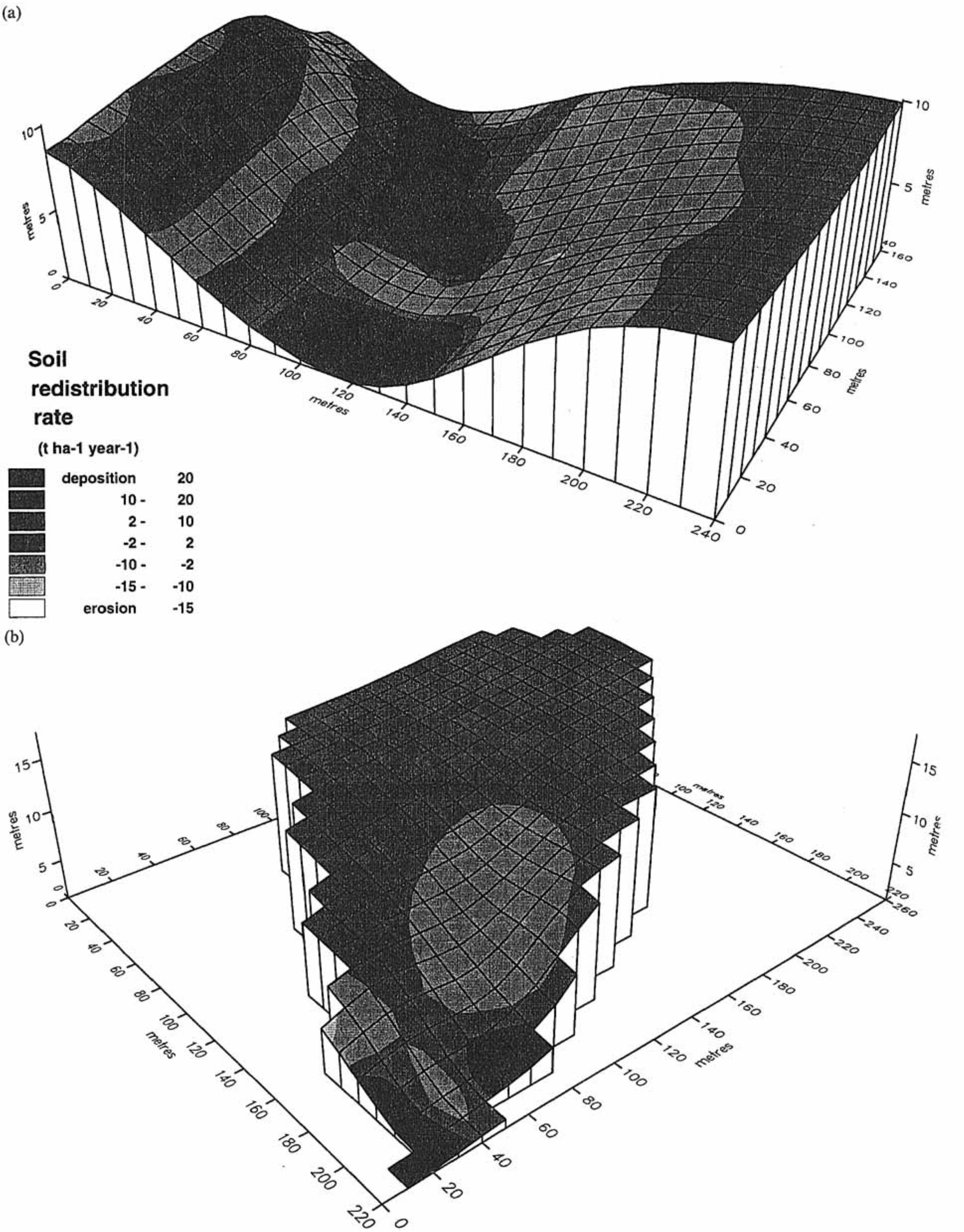


Figure 2. Simulated soil redistribution rates as a result of overland flow ($k_1 = 0$) superimposed over isometric projections of the field topography for the sites at: (a) Rufford Forest Farm and (b) Dalicott Farm

Table II. Results of regression analysis of ^{137}Cs-derived soil redistribution rates with predicted soil redistribution rates ($^{(1)}$, all data points; $^{(2)}$, eroding sites only; significance levels: *, 0·05; **, 0·01; ***, 0·001)

Rufford					Dalicott			
k_1 ($kg\,m^{-1}\,a^{-1}$)	k_3 ($kg\,m^{-2}\,a^{-1}$)	k_3/k_1 (m^{-1})	$r^{2(1)}$ ($n = 113$)	$r^{2(2)}$ ($n = 101$)	k_1 ($kg\,m^{-1}\,a^{-1}$)	k_3 ($kg\,m^{-2}\,a^{-1}$)	k_3/k_1 (m^{-1})	$r^{2(1)}$ ($n = 69$)
0	0·64	∞	0.17***	0·02	0	0·128	∞	0·11*
384	0	0	0·434***	0·35***	404	0	0	0·41***
412	0·051	0·000125	0·45***	0·18***	412	0·051	0·000125	0·45***
348	0·087	0·00025	0·453***	0·34***	397	0·099	0·00025	0·47***
310	0·155	0·0005	0·449***	0·31***	333	0·167	0·0005	0·45***
240	0·24	0·001	0·409***	0·26***	209	0·209	0·001	0·36***
160	0·28	0·00175	0·33***	0·19***	102	0·179	0·00175	0·26***
76	0·266	0·0035	0·24***	0·11***	46	0·16	0·0035	0·187***
18·2	0·228	0·0125	0·16***	0·04	11	0·15	0·0125	0·13**

the predicted zones of maximum erosion lie in areas where slope gradient and contributing area are maximized (mid-slope at Rufford and hollow at Dalicott).

Predicted patterns of diffusive redistribution

Soil redistribution by overland flow may be excluded from the simulation by setting the parameter k_3 to zero. The patterns of soil redistribution obtained using this approach may, therefore, be attributed to diffusive processes and Figure 3 shows the predictions obtained for Rufford and Dalicott. There is clearly a good qualitative agreement between these predictions and the observed patterns shown in Figure 1. In particular, the predicted patterns for diffusive processes show maximum soil loss from the slope convexities and consistent deposition in the concavities. This qualitative agreement is confirmed in a quantitative comparison (Table II) which demonstrates that, in both cases, more than 40 per cent of the variance in observed redistribution rates can be explained by the model of diffusive processes.

Optimum agreement between observed and predicted patterns

For both sites, the agreement between observed (^{137}Cs-derived) and predicted redistribution rates can be improved slightly by including both overland flow and diffusive processes in the simulation. The data in Table II show the improvement in agreement obtained when the processes are combined in the simulation. The improvement is most significant at Dalicott, but the optimum combination of variables is similar at both sites (Rufford: $k_1 = 348$, $k_3 = 0{\cdot}087$; Dalicott: $k_1 = 397$, $k_3 = 0{\cdot}099$). The optimum simulated patterns (Figure 4) illustrate the good agreement achieved but do not demonstrate the relative contributions of overland flow and diffusive processes to the pattern. In order to examine the relative contributions, calculations were made of the fluxes due to overland flow transport and diffusive movement for each grid cell and these were expressed as ratios. The resultant data are illustrated in Figure 5. For both fields, the ratios are considerably lower than one over most of the slope areas indicating that diffusive processes are dominant. Indeed it is only in the main concavities that overland flow is found to be more important than diffusive processes and even there the dominance is not continuous.

DISCUSSION

Comparison of the model simulations with the ^{137}Cs-derived patterns of soil erosion and deposition at both Rufford and Dalicott suggests that soil redistribution at these sites is dominated by diffusive processes. This may seem surprising in view of the known susceptibility of the sites to erosion by water and there is a clear need to consider the reliability and implications of the findings. The discussion will, therefore, focus on three areas: the reliability of the ^{137}Cs approach; the validity of the erosion model; and the possible diffusive processes.

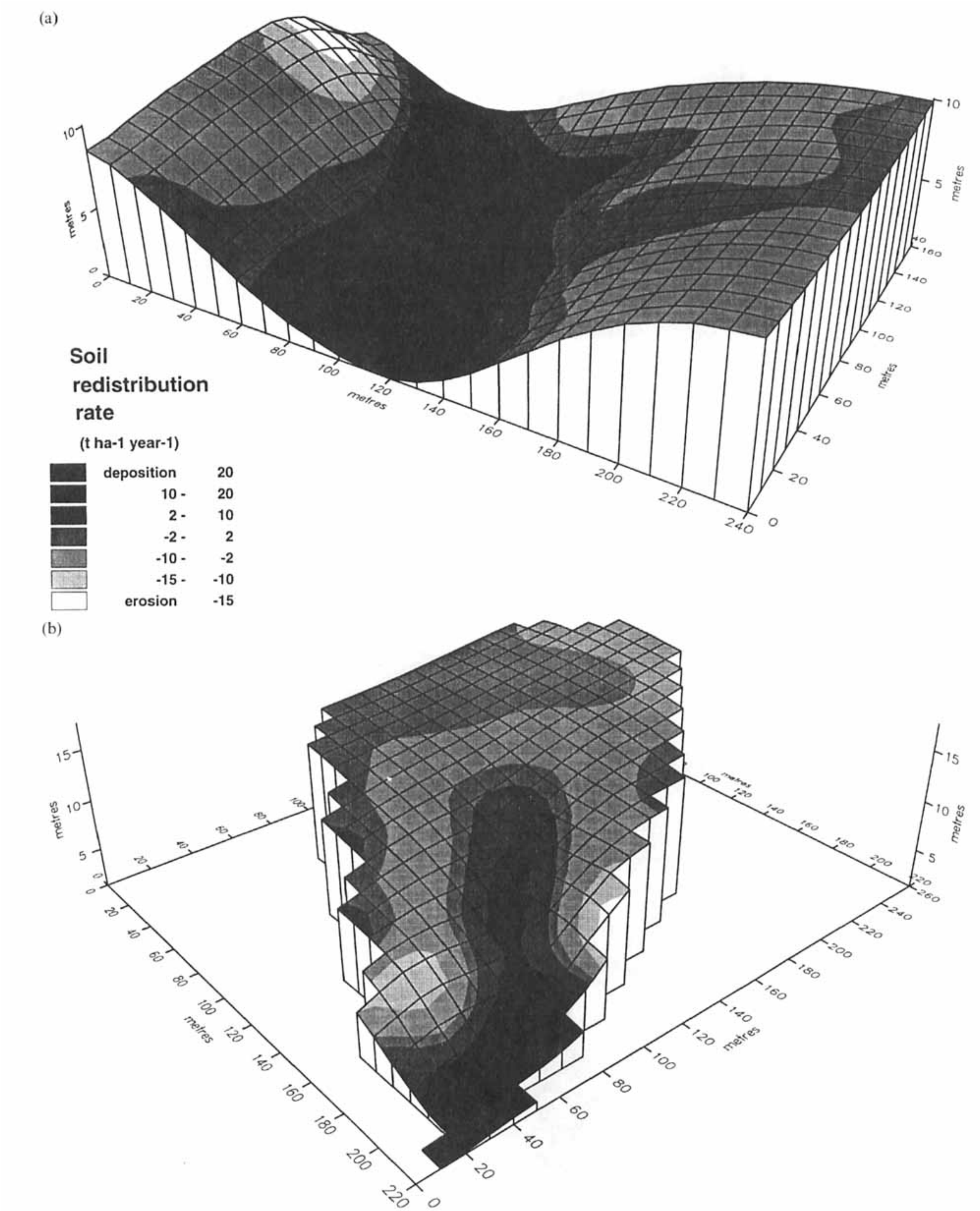


Figure 3. Simulated soil redistribution rates as a result of diffusive processes ($k_3 = 0$) superimposed over isometric projections of the field topography for the sites at: (a) Rufford Forest Farm and (b) Dalicott Farm

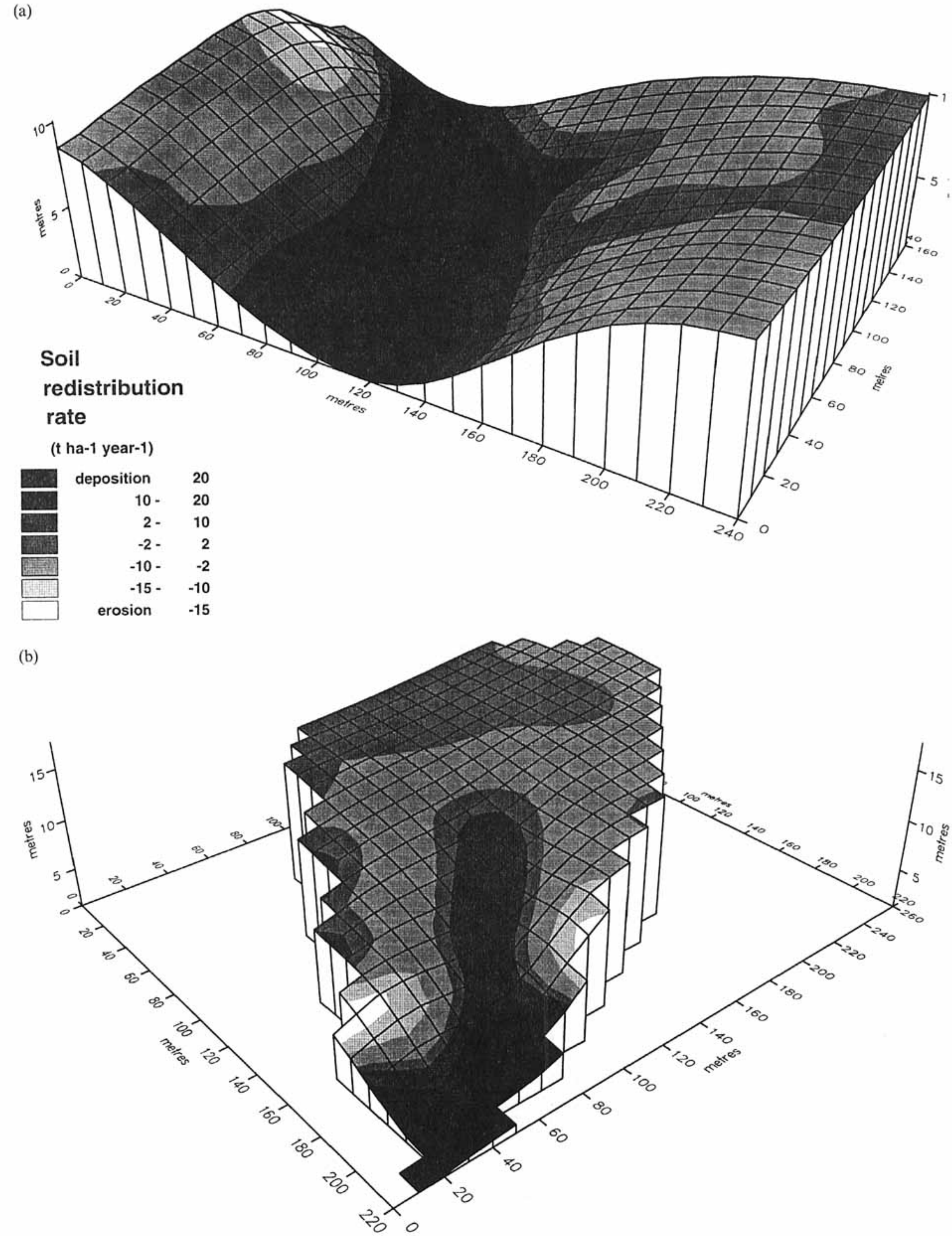
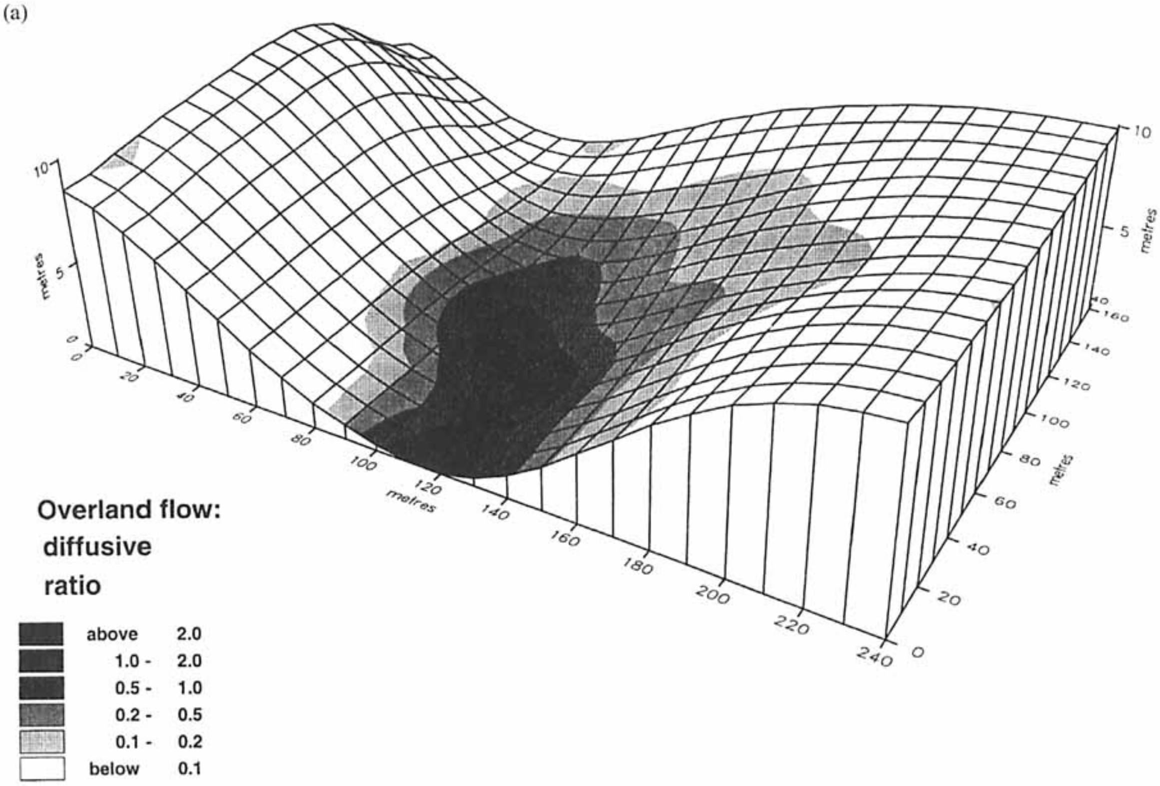


Figure 4. Simulated soil redistribution rates, showing the optimum agreement with the observed (^{137}Cs-derived) data, superimposed over isometric projections of the field topography for the sites at: (a) Rufford Forest Farm ($k_1 = 348$, $k_3 = 0{\cdot}087$) and (b) Dalicott Farm ($k_1 = 397$, $k_3 = 0{\cdot}099$)



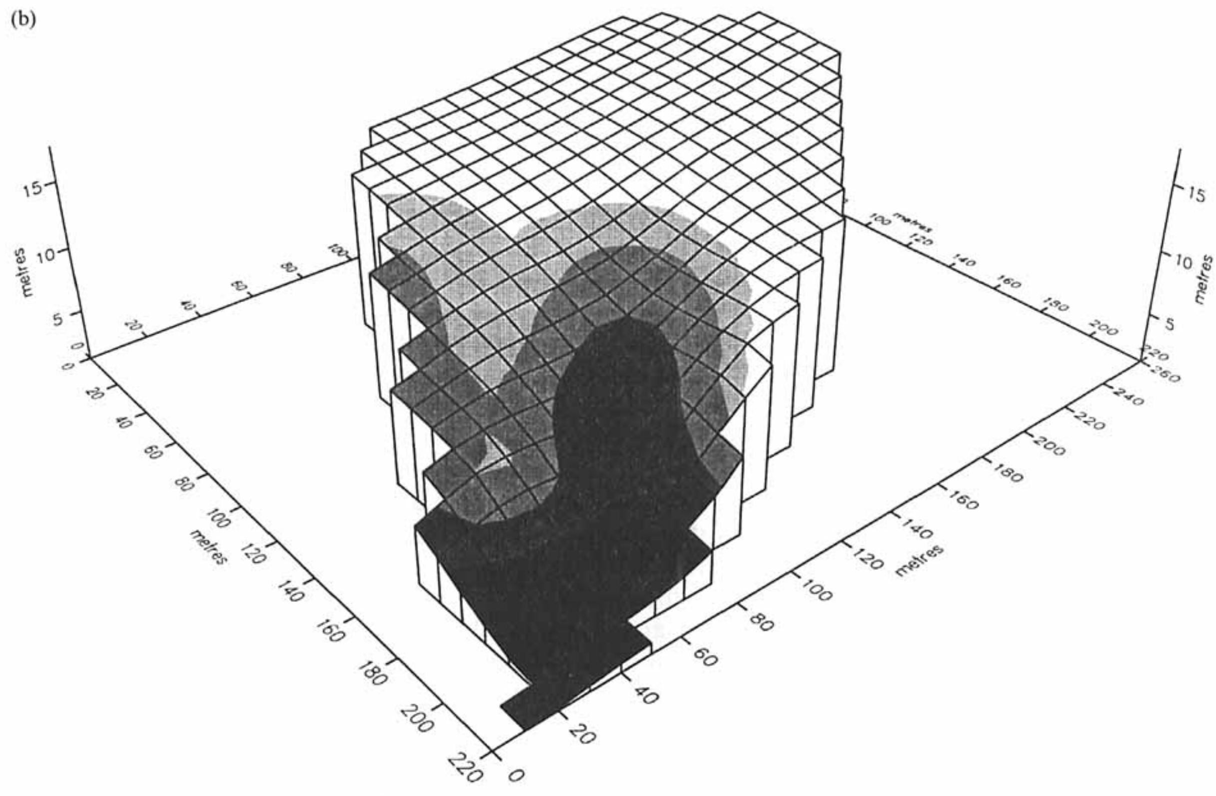


Figure 5. The ratios of overland flow to diffusive soil redistribution, in the optimum simulation, superimposed over isometric projections of the field topography for the sites at: (a) Rufford Forest Farm and (b) Dalicott Farm

The reliability of the caesium-137 approach

The assumption that the ^{137}Cs-derived data represent reliable estimates of long-term soil redistribution is central to the conclusions made regarding the processes operating at the study sites. The reliability of these estimates is, therefore, addressed by reference to the four fundamental assumptions of the ^{137}Cs technique, namely: (i) fallout distributions were uniform at the local scale; (ii) fallout ^{137}Cs was rapidly adsorbed onto soil particles ; (iii) subsequent redistribution of ^{137}Cs took place in association with sediment; and (iv) it is possible to estimate erosion and deposition rates from ^{137}Cs inventories. Although these assumptions have been discussed elsewhere (Walling and Quine, 1992), it may be useful to consider them briefly here.

Of the four assumptions, it is the last which is associated with the greatest uncertainty (Walling and Quine, 1990b). However, this is also the assumption of least importance in the comparison of spatial *patterns*. Furthermore, although estimates produced using different calibration procedures vary in magnitude, such variation is relatively limited and there is increasing evidence for the validity of ^{137}Cs-derived erosion rate estimates (Kachanoski, 1987; Quine and Walling, 1993a; Quine *et al.*, 1994).

Returning to the three remaining assumptions, the weight of both direct and indirect evidence supports their acceptance. Although there is little direct evidence for the initial distribution of fallout ^{137}Cs, systematic variation in fallout at the local scale (<10 ha) seems improbable in the light of the long period of time (in excess of 20 years) over which significant fallout took place (Cawse and Horrill, 1986; Longmore *et al.*, 1983). Instead it seems reasonable to expect that any event-based spatial variation in precipitation and, therefore, fallout would be cancelled out by superposition of the patterns from subsequent storms. The marked spatial variability noted in fallout from the Chernobyl accident may be attributed to both the relatively low level at which the debris cloud circulated and the extremely short period of fallout deposition compared to the long-term bomb-derived fallout used in erosion studies. (There was no significant Chernobyl-derived fallout at either of the sites used in this study.)

In contrast to the limited evidence for spatial variability of long-term fallout deposition, there is ample laboratory and field evidence for the rapid and strong adsorption of ^{137}Cs by mineral sediments of varying textural composition (Livens and Loveland, 1988; Livens and Baxter, 1988; Bachhuber *et al.*, 1983; Evans and Dekker, 1966; Frissel and Pennders, 1982; Walling and Quine, 1992). Furthermore, several experimental studies have demonstrated that subsequent redistribution of ^{137}Cs takes place in association with sediment (cf Bernard and Laverdière, 1993; Rogowski and Tamura, 1970) and a number of field studies have demonstrated the close relationship between ^{137}Cs loss and long-term soil loss (de Jong *et al.*, 1986; Kachanoski, 1987; Quine and Walling, 1993a). However, both field and laboratory studies have demonstrated the close affinity of ^{137}Cs for the silt and clay fractions (Walling and Woodward, 1992) and it is clearly important to consider this factor in conditions where size-selective processes may operate. For example, at a site where both rill and interrill erosion processes occur, locations subject to only interrill (selective) erosion will show proportionately greater ^{137}Cs losses for a given rate of soil loss. Despite the potential non-linearity which this introduces into the relationship between soil loss and ^{137}Cs loss, it is important to note that this relationship will always be positive because a larger soil loss will still cause a larger depletion in ^{137}Cs. Furthermore, this size-selectivity is taken into account in the calibration procedure by incorporation of a rate-proportional selectivity factor in the prediction of the radionuclide content of the eroded sediment. Size-selectivity is also taken into account in the calibration procedure used to estimate deposition rates, by assuming that sediment which is deposited within the field is depleted in ^{137}Cs compared to the eroded sediment. However, it is recognized that spatial variation in the particle size characteristics of deposited sediment within a cultivated field may potentially lead to the existence of a variable and, at worst, non-positive relationship between the excess ^{137}Cs inventory and the depth of deposition. Nevertheless, even if doubt exists concerning the estimates of sediment deposition rates, this cannot influence the similarity between the ^{137}Cs-derived erosion pattern and that predicted for diffusive processes, because the agreement is most obvious in relation to the areas of maximum *erosion*. This conclusion is confirmed by a correlation analysis performed for the data-sets, excluding those points where the ^{137}Cs inventory indicates net soil gain (Table II). This anlaysis demonstrates that the diffusive model explains significantly more of the observed pattern of net *soil loss* than the overland flow model.

On the basis of both previous studies and the internal consistency of the data presented, it appears that the ^{137}Cs approach can provide reliable evidence of the pattern of soil redistribution and a valuable indication of the rates involved.

The validity of the overland flow model

If the reliability of the ^{137}Cs-derived data is accepted then it is important to examine other potential reasons for the apparent dominance of diffusive redistribution of soil within the fields studied. It is, therefore, necessary to consider the validity of the overland flow model. Central to the model is the strong slope-dependence of both rill and interrill erosion and this is supported by evidence from a wide range of sources, including: (i) laboratory experiments using interrill plots (Watson and Laflen, 1986) and examining flow detachment and rill initiation and development (Govers, 1985; Nearing, 1991; Govers, 1991b), (ii) field observations of experimental plots and agricultural land (Smith and Wischmeier, 1957; McCool, 1982; Govers, 1991a); and (iii) theoretical studies (Foster and Meyer, 1975; Moore and Burch, 1986). The model also recognizes the role of slope length and increasing discharge on the rates of rill erosion and this is supported by both experimental studies and field surveys (McCool, 1982; Meyer *et al.*, 1975; Govers, 1991a; Govers and Loch, 1993) although the exact form of the relationship may depend on other factors including soil type, initial soil conditions, etc. (e.g. Duley and Hays, 1937). Therefore, although it is possible that the specific values used for the exponents may not be entirely correct, it may be assumed that the general characteristics of the spatial pattern of erosion and deposition predicted by the model are consistent with the available published data.

Even if very specific hydrological conditions (i.e. a much lower infiltration capacity on the convexities) led to the occurrence of maximum overland flow erosion in areas of maximum slope convexity, the erosion rates suggested by the ^{137}Cs inventories would be inexplicably high. For example, at some locations with very low slope gradients ($<0{\cdot}05$) and short slope lengths (<20 m), where overland flow erosion would be dominated by interrill processes, the ^{137}Cs-derived erosion rates exceed $50\,t\,ha^{-1}\,a^{-1}$, whereas in Gembloux (Belgium), on a very erodible silt loam, Bollinne (1985) measured a mean soil loss of only $5{\cdot}8\,t\,ha^{-1}\,a^{-1}$ over a 3 year period on plots with a length of 22 m and a 0·06 slope. It seems unreasonable, therefore, to accept overland flow erosion as the cause of a mean soil loss which is up to 10 times higher, on a sandy, less erodible soil on even lower slopes and under comparable climatic conditions.

Possible diffusive processes

If both the reliability of the ^{137}Cs approach and the validity of the model are accepted then it must be concluded that diffusive processes dominate soil redistribution at both Rufford and Dalicott. It is, therefore, necessary to identify potential diffusive processes and consider whether they can explain the magnitude of the observed soil redistribution. The best-known examples of diffusive processes, namely rainsplash and soil creep (Kirkby *et al.*, 1987), will be considered first and then attention will turn to tillage. In order to assess the capacity of each process to explain the magnitude of the observed soil redistribution, the diffusion constant k_1 has been estimated for each process. The values identified may be compared with the best estimates used in the simulation which lie in the range $350–400\,kg\,m^{-1}\,a^{-1}$.

The quantities of soil detached by raindrop impact on agricultural land can be very considerable and may well exceed $100\,t\,ha^{-1}\,a^{-1}$ on silty loamy soils (Bollinne, 1978; Govers 1991c). However, direct downslope movement of soil material remains rather limited. For example on the highly erodible soils of the Huldenberg experimental field near Leuven (Belgium), Govers (1991c) measured a mean splash detachment rate of $15{\cdot}2\,kg\,m^{-1}$ from September 1983 to October 1984. Using the model developed by Poesen (1986) this can be converted to a downslope flux of *c.* $1{\cdot}85\,kg\,m^{-1}a^{-1}$ on a 0·2 slope, which corresponds to a diffusion constant of $9{\cdot}25\,kg\,m^{-1}a^{-1}$.

As has been indicated, soil creep may also be viewed as a diffusive process. On cultivated fields, it may be assumed that most soil creep will result from the loosening of the topsoil by tillage and its subsequent settling during the growing season. This settling may lead to an increase in the soil bulk density of up to 20 per cent. If it is assumed that soil loosening occurs in a direction perpendicular to the soil surface and that soil settling takes place in the vertical direction, and that the topsoil has a depth of 0·25 m, the soil creep due to this process will result in a net downward flux of $1{\cdot}3\,kg\,m^{-1}\,a^{-1}$ on a 0·2 slope, corresponding to a diffusion constant of *c.* $6{\cdot}5\,kg\,m^{-1}\,a^{-1}$.

Both splash and creep may have actively contributed to soil redistribution on the studied fields. However, these processes will generally cause redistribution rates of some tens of kilograms per hectare per year and the low diffusion constants indicate that they cannot explain the magnitude of the observed soil redistribution. It is, therefore, clear that a diffusive process which is capable of significant soil redistribution must be identified.

Recently, several authors have drawn attention to the fact that tillage may make a major contribution to soil redistribution on arable land (Lindstrom *et al.*, 1992; Govers *et al.*, 1993; Revel *et al.*, 1993; Govers *et al.*, in press; Quine *et al.*, 1994). Net soil redistribution due to tillage is thought to result from the greater downward displacement of soil during a downslope tillage operation than the upward displacement during the complementary upslope operation. This may seem obvious when tillage is carried out along a line perpendicular to the contour, but it will also take place when tillage is carried out along the contour line when a mouldboard plough or a similar implement is used, causing significant lateral movement of the soil (Lindstrom *et al.*, 1992; Govers *et al.*, 1994). Although experimental studies of tillage are limited, the available data show great consistency. In a recent study, Govers *et al.* (1994) employed both experimental data and existing published information to demonstrate that tillage can be modified as a diffusive process, because a linear relationship exists between the mean net displacement distance and the slope gradient. The intensity of the process may be characterized by the value of the diffusion constant calculated on a per tillage operation basis. Table III shows that a yearly mouldboard tillage operation alone corresponds to a diffusion constant of *c.* 300 kg m^{-1} a^{-1}. If the additional soil movement caused by harrowing etc. is taken into consideration it is clear that the tillage process is both of the correct type and of the required order of magnitude to explain the observed soil redistribution on these fields. Furthermore, the potential impact of tillage even when using animal traction is demonstrated by Quine *et al.* (1993) who identified a diffusion constant of *c.* 250 kg m^{-1} a^{-1} on a terraced field in the Loess Plateau, China. The magnitude of soil redistribution due to tillage can be illustrated by the following example: on a convex slope of 100 m length with a zero slope at the upslope end and 0·2 slope at the downslope end, the net downslope movement of soil due to mouldboard tillage and harrowing will correspond to 6–8 t ha^{-1} a^{-1}. Thus, on local convexities soil losses exceeding 10 t ha^{-1} a^{-1} are entirely reasonable.

Erosion processes operating in the fields

The preceding results strongly suggest that tillage is the major agent of soil redistribution operating within the studied fields. However, they do not imply that water erosion can be neglected and, as has already been shown, the optimum agreement between observed and predicted patterns is associated with a combined diffusion–overland flow erosion model. This is most evident for the Dalicott field: if only diffusion-type movement is assumed, high deposition rates are predicted in the hollow (Figure 3b), while in reality no, or very little, deposition is found there (Figure 1b). It appears, therefore, that the infilling of the hollow by tillage processes is compensated by soil export by water erosion concentrated in this area. In this case

Table III. Values of k_1 derived from the experiments of Lindstrom *et al.* (1992), Govers *et al.* (in press) and Revel *et al.* (1993)

Type of experiment	k_1 (kg m^{-1} per tillage operation)
Mouldboard plough up- and downslope (Govers *et al.*, in press)	234
Chisel plough up- and downslope (Govers *et al.*, in press)	111
Mouldboard plough across the slope (Lindstrom *et al.*,1992)	363
Mouldboard plough up- and downslope (Lindstrom *et al.*, 1992)	330
Mouldboard plough up- and downslope (Revel *et al.*, 1993)	263

tillage may be seen as a contributor both to soil redistribution itself and to the supply of erodible sediment to areas which are susceptible to water erosion.

Another factor which may be of relevance to soil and ^{137}Cs budgets on cultivated land is the loss of soil with the harvest of root crops. Vanden Berghe and Gulinck (1987) report that soil losses due to cropping of sugar beet and potatoes may average up to 5 t ha^{-1} a^{-1}. These losses may to some extent explain why both of the fields in this study show a rather high net ^{137}Cs and soil loss, despite the moderate impact of water erosion. Crop-associated soil losses may be assumed to be more or less uniform over the whole field, leading to a uniform percentage reduction in ^{137}Cs inventories and no significant impact on the pattern caused by spatially varying processes.

IMPLICATIONS

Both the evidence from previously reported soil tillage experiments (Lindstrom *et al.*, 1992, Revel *et al.*, 1993; Govers *et al.*, 1994) and the results from the modelling of spatial patterns of soil redistribution presented above suggest that soil tillage is an important geomorphic process on arable land. Erosion and deposition rates associated with tillage erosion may often exceed 10 t ha^{-1} a^{-1}, especially on irregular terrain. Such rates are at least of the same order of magnitude as average water erosion rates reported for hilly cropland in western Europe (e.g. Bollinne, 1985; Schaub, 1989; Boardman, 1990; Govers, 1991a; Vandaele, 1993; Auzet *et al.*, 1993). Soil tillage should, therefore, be considered as an erosion process *per se* and not merely as an operation making the soil more vulnerable to water erosion. Indeed, in many areas of intensive agriculture with a temperate climate, within-field rates of soil redistribution due to tillage are probably significantly greater than those due to water erosion and sedimentation. Thus, tillage should be considered as an important factor in soil degradation. At present, this is not well perceived: in the GLASOD (Global Assessment of Soil Degradation) project, soil erosion by tillage implements is not taken into account (Olderman *et al.*, 1990).

The fact that soil movement by tillage may be described by a diffusion-type equation also implies a characteristic soil redistribution pattern with erosion taking place on the convexities and sedimentation occurring in the concavities. This has important implications for the identification of areas which are most susceptible to long-term erosion (Quine and Walling, 1993b). Absolute values of slope gradient and/or slope length, which are usually considered to be the dominant topographic controls on water erosion, are irrelevant for tillage, because the erosion/deposition pattern is controlled by the *change* in slope-gradient.

Recognition of tillage as an agent of soil redistribution is also important for geomorphologists. Firstly, as noted above, tillage may counteract the geomorphic effects of fluvial processes. Therefore, even in environments characterized by rill and gully incision, the long-term trend in landform evolution may be towards reduction in relief rather than increase (Quine *et al.*, 1994). Secondly, because tillage will only redistribute soil within a field, each field boundary will also be a line of zero flux. Consequently, on sloping land, soil will be deposited along the upslope edge of the field boundary while erosion will occur along the downslope edge, thereby creating soil banks. For example, Papendick and Miller (1977) report that soil banks 3–4 m high were formed by tillage in Washington, USA. Tillage may, therefore, be seen as an important geomorphic agent.

Finally, significant soil movement by tillage has implications for both archaeologists and soil scientists. For example, coarse fragments (e.g. archaeological remains) may become dispersed over larger areas or transported downslope from their original location (Reynolds, 1988, Van Peer, pers. comm.). Disturbance of a stony soil by tillage may also cause a net upward movement of the coarse fragments thereby contributing to the formation of a stone pavement (Kouwenhoven, 1979).

CONCLUSIONS

The available experimental and theoretical evidence strongly suggests that soil tillage is the dominant geomorphic process operating on the fields investigated in this study. Furthermore, this may well be true of the

majority of the arable land in western Europe, at least if soil redistribution within the field is considered. Therefore, only if off-site impacts are of greatest concern should attention focus on aeolian and fluvial processes in isolation. In contrast, if soil loss, reduced productivity and other on-site impacts are the primary concerns, attention should focus on tillage erosion and the areas at most risk, namely slope convexities and upslope boundaries.

Furthermore, studies of landscape evolution on agricultural land should take into account the invisible impact of tillage in addition to the often dramatic evidence of water erosion (Poesen and Govers, 1990; Auzet *et al.*, 1993; Vandaele, 1993). While landscapes dominated by overland flow erosion will tend towards incision and increase in relief, those dominated by tillage will tend towards infilling and relief reduction. Both this and other studies (Govers *et al.*, 1993; Revel *et al.*, 1993; Quine *et al.*, 1993, 1994) indicate that tillage dominance may be more common than is currently perceived.

The identification of the tillage effect on soil redistribution was only possible by using a tracer providing information on the spatial pattern of soil redistribution over a longer period of time and comparing these results with predictions based on steady-state, but spatially distributed models, as well as experimental results. This highlights both the potential of the ^{137}Cs technique in soil erosion research and the considerable advantages to be obtained by the combination of diverse data sources. It is believed that further improvement in our understanding of soil redistribution patterns on sloping arable land will not in the first place result from further model sophistication. Instead, more effort should be devoted to collection of detailed topographic data and selection of sampling sites to investigate the response of the various sediment fluxes to topographic variations. Interpretation of results could also be improved by collecting experimental data on the impact of selective erosion and deposition on the redistribution of ^{137}Cs. This would allow further refinement of the calibration procedures.

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